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ARTICLE

# Measuring the Economic Value of Increased Precision in Scientific Estimates of Marine Mammal Abundance and Bycatch: Harbor Porpoise *Phocoena phocoena* in the Northeast U.S. Gill-Net Fishery

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***Abstract***
**Marine mammal stock assessments provide information that is valuable to public sector management and the private fishing sector; however, data are costly to collect. The precautionary approach, which is widely used in fishery and marine mammal management, advocates a conservative management decision with priority to the resource when there is uncertainty regarding the impact on the resource from human activity. The potential biological removal (PBR) control rule of the U.S. Marine Mammal Protection Act explicitly incorporates uncertainty in input variables into the determination of allowable levels of human-induced mortality for a stock. Less uncertainty results in higher PBR values for a given stock level. Variations in government funding levels can disrupt the scientific data collection that is necessary for PBR calculation. We present an economic net benefit framework that examines the indirect value of information from marine mammal stock assessments to the commercial fishing industry. Using the harbor porpoise *Phocoena phocoena* and the U.S. Atlantic sink gill-net fishery as a case study, we estimated the difference between total public sector data collection costs and total private sector benefits from increased profits. Net benefits represent a measure of the value of information to society, while the difference in profits measures the value of the information to the private sector. Several results are forthcoming. First, the optimal allocation of funding showed that abundance surveys are a more cost-effective means to reduce uncertainty in PBR input variables than increasing observer coverage of the fishing industry. Second, for all levels of PBR in this empirical example, total benefits to the private sector for a higher PBR exceeded the costs of collecting additional scientific data to increase the precision of input variables and thus increase PBR. Since net benefits are positive, the private sector may consider funding of scientific data collection for marine mammals as a way to reduce uncertainty, thereby allowing a higher PBR value.**

The management of marine resources can create costs for both the public and private sectors. The public sector provides funds for biological assessments to determine population levels and a sustainable level of human impacts. Biological assessments rely on sampling data, which introduce uncertainty into stock assessment estimates. The precautionary approach, which is widely used in fishery and marine mammal management, advocates a conservative management decision with priority to the resource when there is uncertainty regarding the impact on the resource from human activity (FAO 1996; Hildreth et. al. 2004). In general, the greater is the uncertainty, the greater are the restrictions and the greater are the costs to industry. However, there are costs associated with reducing uncertainty, such as the costs of collecting data to increase the precision of stock estimates.

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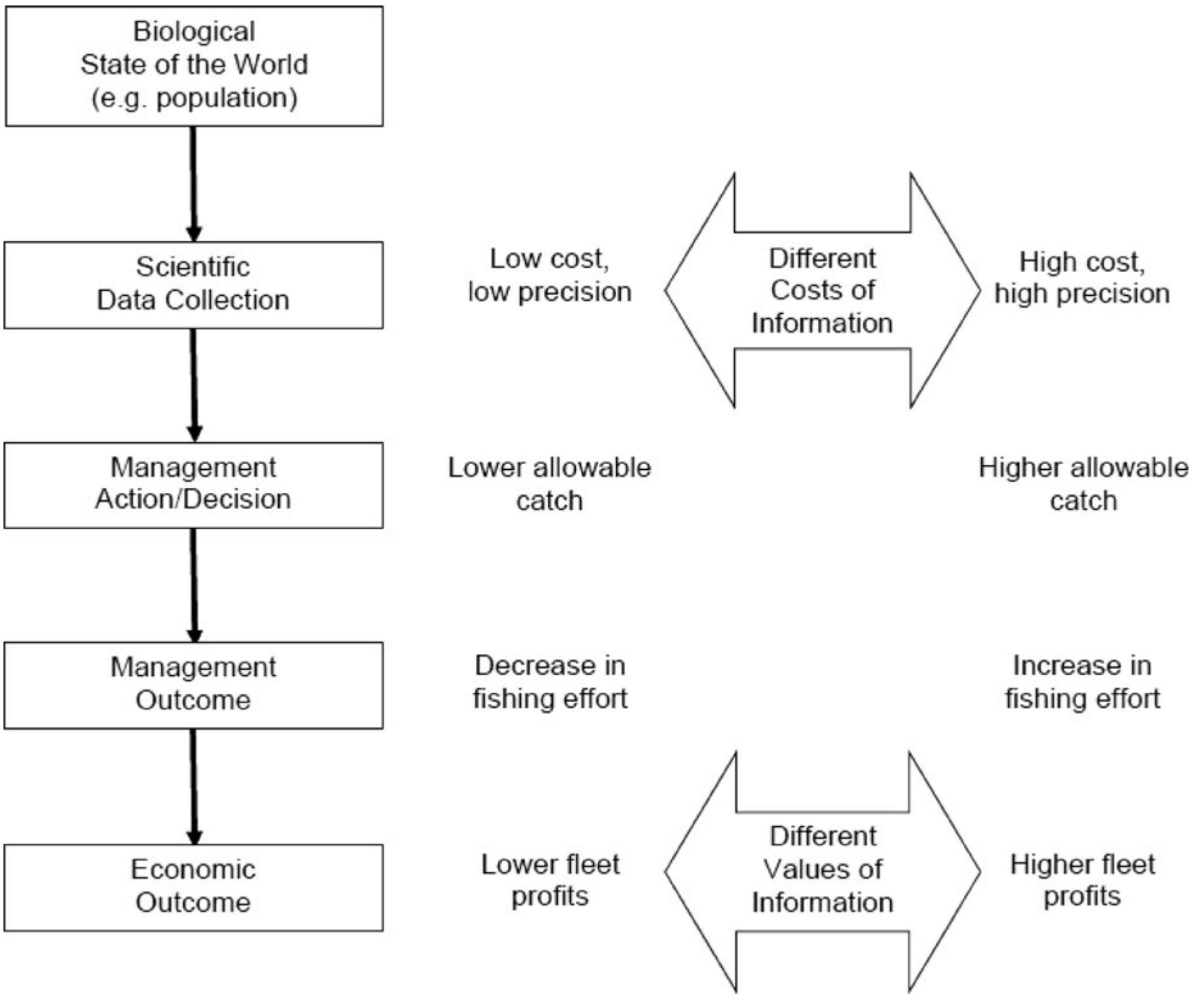


FIGURE 1. A framework for measuring the value of scientific information based on the link between management actions and economic outcomes.

This suggests the existence of an economic tradeoff between the value placed by the private sector on a reduction in scientific uncertainty and the higher public costs of collecting additional scientific data to increase the precision of the information.

The economic tradeoffs between the costs and benefits allow us to identify a value for scientific information through the link between management actions and economic outcomes (Figure 1). There is uncertainty in the biological state of the world, and we use scientific data collection to describe that state. The public sector has a choice to use a low-cost or high-cost measurement system, resulting in lower or higher precision, respectively. The scientific information gains value for the private sector through the impact of that information on management actions or decision rules (Huppert 1996). The management outcome is a behavioral change in the managed sector (e.g., a change in fishing effort). In this context, the scientific information has value since it triggers management decisions that affect the economic outcomes (e.g., fishing profits); the larger the effect, the greater is the benefit or value of the information. Different levels of precision in scientific information will result in different economic outcomes and thus will have different values to the private sector depending on the degree of impact. For example, a fishery may respond to decreases in allowable catch by changing the amount and location of fishing effort (management outcome), which may reduce profitability (economic outcome) and the future stream of benefits.

Balancing the value of additional information with the cost of collecting that information is an ongoing issue in resource management; however, determining the balance may be especially challenging in marine mammal science. For species that are not commercially harvested or that are bycatch with no market price, such as marine mammals, the value of additional scientific information must be estimated indirectly. This leads to greater difficulty in measuring the link between the management outcome and the economic outcome. Here, we present an economic net benefit framework that examines the indirect value of information from marine mammal stock assessments to the commercial fishing industry. The government is responsible for marine mammal monitoring and survey activities that directly influence the bycatch restrictions placed on the fishing industry. The difference in profits under alternate states of high and low precision provides a measure of the value of scientific information to the industry. This value minus the costs to collect the information provides a partial measure of the net benefits of the information to society.

The U.S. Marine Mammal Protection Act (MMPA) was enacted in 1972 and established a long-term regime for governing interactions between marine mammals and commercial fishing operations. The potential biological removal (PBR) control rule was enacted under the MMPA in 1994 and specifies the allowable level of human-induced mortality for a marine mammal stock (MMPA 1972, section 1386). When the 5-year average of the annual bycatch estimate is greater than PBR, the stock is designated "strategic." The National Marine Fisheries Service (NMFS) must convene a take reduction team (TRT), which has 6 months to develop a take reduction plan (TRP). The TRP must reduce bycatch below PBR within 6 months of implementation, with a long-term goal of reducing bycatch to insignificant levels approaching zero. The objective of the TRT process is to identify policy alternatives that achieve a given level of conservation (i.e., bycatch below PBR) in a cost-effective manner (see NOAA 2009 as an example). In general, most of the costs associated with a reduction in bycatch are borne by private entities (e.g., fishers) through a combination of direct costs (e.g., gear modifications) and harvest reductions (e.g., closed times or areas, or use of less-efficient gear). For example, the TRPs for harbor porpoises *Phocoena phocoena* in the Gulf of Maine and for Atlantic coastal bottlenose dolphins *Tursiops truncatus* combine gear modifications with seasonal–spatial closures to reduce the incidental take in high-bycatch areas (Resolve 1996; NOAA 2006, 2009). The TRP for false killer whales *Pseudorca crassidens* in the Pacific identified gear modifications as the cost-effective solution (NOAA 2012). In general, less-stringent PBR constraints result in lower costs to the industry.

Potential biological removal is a conservative measure that errs on the side of marine mammal protection by decreasing when uncertainty is high, as measured by the CVs for the abundance and bycatch estimates (Wade and Angliss 1997). The three components of the PBR calculation are based on abundance estimates, bycatch estimates, and life history assessments. These components are derived from data collected during abundance surveys, observer trips aboard fishing vessels, and a combination of carcass necropsies and longitudinal live-animal studies, respectively (Waring et al. 2009). In the USA, these activities are publicly funded. For a given population and with constant environmental factors, higher expenditures on surveys and observer trips generally increase the precision of the variables that are used to calculate PBR. Legislation and budgets determine the level of funding, which affects the scale, intensity, and frequency of research assessments and observer coverage but may not take into account the indirect economic impacts of those decisions. A lack of consistent funding necessitated the development of management guidelines to address outdated stock assessments (U.S. Department of Commerce 2012), although economic aspects are not considered. We present a framework for comparing the public cost to improve the precision of variables used to calculate PBR and the private sector benefits that accrue due to fishing effort changes from a higher PBR value. We illustrate the framework by using a case study of the harbor porpoise and the U.S. Atlantic coast sink gill-net fishery, which are described by rich data sets that facilitate our investigation.

Throughout this analysis, the PBR values discussed are consistent with the requirements set out in the MMPA—that is, higher or lower values of PBR result only from changes in input variables for the current PBR model. This assumes that the true population level does not change and that the level of protection provided by constraining mortality to PBR allows a sustainable source of mortality that is appropriate for protection of the population. Furthermore, it is assumed that the level of protection provided by PBR is acceptable to society and that the actual value of PBR does not affect this level of social acceptance.

We first present background information about our case study (management of harbor porpoises and the northeast U.S. gill-net fleet) and detailed information on the PBR calculation. We then explain the methods that are used to solve the public and private sector problems and develop the means to compare tradeoffs between them. Results and discussion follow.

## BACKGROUND

### Harbor Porpoise Management under the Marine Mammal Protection Act

There are four harbor porpoise populations in the northwest Atlantic (Waring et al. 2009). This study focuses on the Gulf of Maine/Bay of Fundy (GOM/BOF) population, which is found in the USA from North Carolina to Maine during the fall and winter. In the late spring, harbor porpoises within the GOM/BOF population migrate northward out of U.S. waters and mate in the BOF area of Canada during the summer. A single PBR value is calculated for the GOM/BOF population throughout its U.S. range, and the value is re-estimated as new scientific data become available. Since 1998, PBR has both increased and decreased (Figure 2). Both the PBR increase in 2000 and the decrease in 2006 were due to updates in abundance estimates from new surveys. In 2009, PBR increased by 98 animals due to new scientific results on the maximum theoretical productivity rate for the harbor porpoise (Moore and Read 2008); revisions of the maximum productivity rate are a rare occurrence.

Observers in the northeast USA have found harbor porpoises caught incidentally only in gill nets. Harbor porpoises can be entangled in the gear and suffocate. Sink gill-net vessels operate from Maine to North Carolina year-round (Bisack and Sutinen 2006). Vessels leave port in the morning, haul and reset their gear, and return to port the same day. Target species landed by this fleet include Atlantic Cod *Gadus morhua*, Spiny Dogfish *Squalus acanthias*, Pollock *Pollachius virens*,

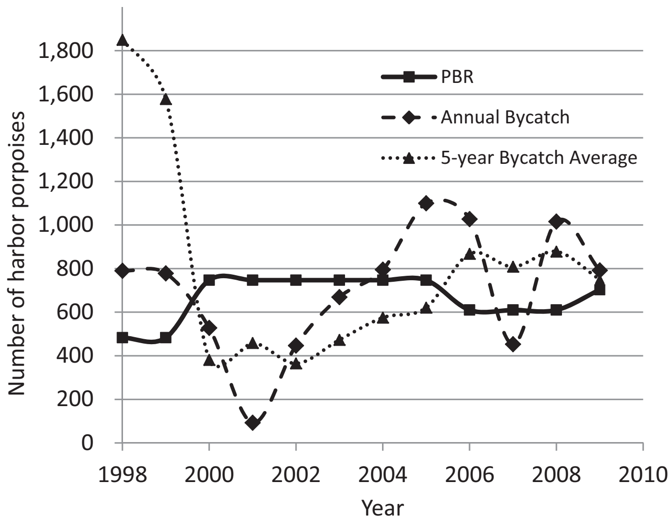


FIGURE 2. Potential biological removal (PBR) value for the Bay of Fundy/Gulf of Maine harbor porpoise stock (diamonds), total annual bycatch estimates (squares), and the 5-year average annual bycatch (triangles) from 1998 to 2009. Changes in PBR are due to updated abundance estimates (in 2000 and 2006) and an increase in the maximum productivity rate (in 2009).

Goosefish *Lophius americanus* (also referred to as "monkfish"), and flounders (Pleuronectiformes). The mix of species landed varies by season and area.

Each year, the National Oceanic and Atmospheric Administration (NOAA) estimates the bycatch of harbor porpoises from the GOM/BOF population in the North Atlantic sink gill-net fishery, with separate estimates for the fishery from Maine to Connecticut (the northeast) and from New York to North Carolina (the Mid-Atlantic). During the last decade, there has been a cycle in which total harbor porpoise bycatch moved above and below PBR as both values moved up and down (Figure 2). Annual estimates of bycatch mortality vary due to a number of factors, including changes in fishing effort and practices, observer sampling, and movement of harbor porpoises. These factors directly influence the CV for the bycatch estimate.

The 5-year average bycatch mortality was above PBR from 1998 to 2000, at which point it dropped below PBR with implementation of the first TRP in 1999 (U.S. Department of Commerce 1998). The TRP created seasonal closed areas and required fishers to attach acoustical devices (pingers) to their nets so as to deter harbor porpoises from approaching the fishing gear. In 2006, the 5-year average mortality once again exceeded PBR, and in 2007 the TRT reconvened to develop a new plan (U.S. Department of Commerce 2010). Data on the new plan were not available for incorporation in this analysis.

## Potential Biological Removal Calculation

Potential biological removal is defined in the MMPA as "the maximum number of animals, not including natural mortalities, that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population." The equation used to calculate PBR is

$$\mathrm{PBR} = N_{min} \times 0.5R_{max} \times Fr, \tag{1}$$

where $N_{min}$ is the minimum population estimate, $R_{max}$ is the maximum theoretical or estimated net productivity rate of the stock at a small population size, and $Fr$ is a recovery factor. The goal of PBR is to allow each stock to reach or maintain a population level above the maximum net productivity level. A conservative surrogate for a known net productivity rate at the maximum net productivity level is provided by $0.5R_{max}$, which is based on biological data.

The $Fr$ is set at a value between 0.1 and 1.0. Setting $Fr$ to less than 1.0 allocates a proportion of the expected net production to population growth. In general, for endangered stocks, $Fr$ is set at 0.1; however, $Fr$ is a parameter that allows managers to account for uncertainties in addition to abundance estimate precision, such as a lack of full knowledge about stock boundaries (Wade 1998). For stocks with bycatch estimates, guidance on the calculation of PBR allows the $Fr$ value to directly take into account the uncertainty in the bycatch estimate ($B$), as measured by the CV of the average bycatch estimate ($\mathrm{CV}_B$). The $\mathrm{CV}_B$ is a function of the number of observed fishing trips, with the value decreasing as more trips are observed. As the precision of the bycatch estimate decreases (i.e., $\mathrm{CV}_B$ increases), a larger portion of expected net production is allocated to population growth. The suggested adjustments to $Fr$ for threatened or depleted stocks (e.g., harbor porpoises; NMFS 2005) are as follows: (1) when $\mathrm{CV}_B \leq 0.3$, set $Fr$ at 0.5; (2) when $0.3 < \mathrm{CV}_B \leq 0.6$, set $Fr$ at 0.48; (3) when $0.6 < \mathrm{CV}_B \leq 0.8$, set $Fr$ at 0.45; and (4) when $\mathrm{CV}_B > 0.8$, set $Fr$ at 0.4.

The calculation of $N_{min}$ incorporates both the precision and variability ($\mathrm{CV}_{Nbest}$) of the abundance estimate ($N_{best}$). Specifically, the calculation is

$$N_{min} = \frac{N_{best}}{e^{\left\{z*\sqrt{\log_e[1+(\mathrm{CV}_{Nbest})^2]}\right\}}}. \tag{2}$$

Consistent with MMPA definitions, $N_{min}$ is calculated such that a stock of unknown status would achieve and be maintained at the optimal sustainable population with 95% probability (NMFS 2005). Population simulations have demonstrated that this goal can be achieved by defining $N_{min}$ as the 20th percentile of a lognormal distribution based on an estimate of the number of animals in a stock (Wade 1998). This is equivalent to the lower limit of a 60% two-tailed confidence interval, where the standard normal variate $z*$ is equal to 0.842.

## DATA AND METHODS

In this section, we develop a framework for assessing the costs and benefits of precision sampling for harbor porpoises by using $\mathrm{CV}_{Nbest}$ and $\mathrm{CV}_B$ as metrics for the level of uncertainty. We do not attempt to develop a full cost–benefit analysis for harbor porpoise management, as that is beyond the scope of the present paper. Three steps are required in the estimation of the cost and benefit tradeoffs. First, we determined an efficient, least-cost allocation of public sector expenditures for abundance surveys and observer trips by resolving the problem for given PBR levels. Second, we used a previous numerical bioeconomic model (Bisack and Sutinen 2006) to estimate changes that occur in gill-net fleet profits as the allowed harbor porpoise bycatch cap changes. Finally, we used the difference between public sector costs and private sector benefits to obtain an estimate of the net benefits (NB), or the value of additional information for reducing uncertainty at different PBR levels.

## Costs for Information Collection

The cost-minimization problem brings together the uncertainty in the abundance and bycatch estimates, the role of this uncertainty in the PBR calculation, and the cost of collecting the data necessary for the estimates. We consider only the direct costs associated with acquiring biological data. We use several years of aerial abundance survey data to model the relationship between the precision of the harbor porpoise abundance estimate (i.e., $CV_{Nbest}$) and the total kilometers of trackline surveyed (explained below). Similarly, we estimate the relationship between the precision of the bycatch estimates (i.e., $CV_B$) and the number of observed fishing trips. In general, large-scale survey sampling effort can be partitioned into several homogeneous strata to minimize the overall CV of the total abundance or bycatch estimate. We assume that a similar methodology is used at all scales so that changes in CV are strictly the result of additional tracklines and observer trips. These two survey relationships are brought together in a nonlinear cost-minimization model to estimate the least cost combination of activities for a given PBR level.

This analysis does not consider public sector administrative and management costs for the TRT process, which were estimated to require \$150,000 in direct costs for face-to-face meetings during 2007 (A. Johnson, NMFS, Greater Atlantic Regional Fisheries Office, personal communication). Although these costs are substantial, they do not directly influence scientific sampling decisions or the profits earned in the sink gill-net fishery.

*Abundance surveys*.—The most recent $N_{best}$ of 89,054 harbor porpoises ($CV_{Nbest} = 47\%$) was based on a 2006 survey of 10,676 km of trackline (Palka 2006). The $N_{best}$ and $CV_{Nbest}$ influence PBR through the calculation of $N_{min}$. We assume a constant $N_{best}$ of 89,000 animals, allowing only the $CV_{Nbest}$ to vary. This is a simplification since $N_{best}$ is likely to change as the $CV_{Nbest}$ changes; however, allowing for changes in $N_{best}$ complicates the presentation without significantly adding to the framework.

To estimate marine mammal abundance, NOAA conducts surveys to collect data by using ships, planes, or both. Since 1994, all PBR values for harbor porpoises have been based solely on aerial surveys. In this analysis, we use only the results from the single-species aerial surveys conducted between 1999 and 2006 (Palka 2006, 2012), which allows comparability of the multiple data points.

TABLE 1. Observed harbor porpoise abundance estimates ($N_{best}$), CV of abundance estimates ($CV_{Nbest}$), kilometers of trackline flown ($L$), other key variables (TSD = total survey days; $\delta$ = days allocated to observer training and transit between survey points; $\beta$ = observed number/percentage of nonsurvey days due to poor weather conditions; $\alpha$ = average kilometers of trackline surveyed per day), total survey cost, and average cost per kilometer flown for aerial surveys of harbor porpoises in the northwest Atlantic during 1999–2006 (D. Palka, NMFS, Northeast Fisheries Science Center, personal communication).

| Variable | 1999 | 2002 | 2004 | 2006 |
|---|---|---|---|---|
| $N_{best}$ | 22,255 | 64,047 | 51,520 | 89,054 |
| $CV_{Nbest}$ (%) | 76 | 48 | 65 | 47 |
| $L$ (km) | 5,649 | 7,465 | 6,097 | 10,676 |
| TSD | 23 | 29 | 31 | 34 |
| Achieved TSD | 8 | 12 | 13 | 18 |
| $\delta$ | 2 | 2 | 3 | 4 |
| $\beta$ in days | 13 | 15 | 16 | 12 |
| $\beta$ as a percentage of TSD | 57 | 52 | 48 | 35 |
| $\alpha$ | 706 | 622 | 469 | 593 |
| Total survey cost (\$)[a] | 95,000 | 120,000 | 145,000 | 140,000 |
| Average cost per kilometer flown (\$) | 17 | 16 | 24 | 13 |

[a]The trackline cost includes the labor costs for pilots and marine mammal observers, plane rental costs, and fuel consumption as well as other direct overhead costs identified above (Palka, personal communication).

Aerial abundance surveys are preplanned and prepaid. The line length ($L$) to be surveyed depends on the desired level of precision for the abundance estimate, the estimated encounter rate of the animals, and the CV for the encounter rate. Encounter rate values are typically available from pilot study data or previous surveys. Aerial survey costs are based on the total survey days, which incorporate $L$, the average kilometers of trackline surveyed per day ($\alpha$), the expected percentage of nonsurvey days due to poor weather conditions ($\beta$), and the number of days allocated to observer training and transit between survey points ($\delta$; Buckland et al. 1993). This analysis assumes that with an increase in $L$, all other variables remain unchanged. For the harbor porpoise aerial surveys, the planner typically assumes that 50% of the sea days will be bad weather ($\beta = 0.5$), and historical survey data indicate that the Twin Otter plane can survey roughly 600 km/d. The $\beta$ value may be set at different levels in different regions, with the value generally higher in the northeast than in other U.S. regions, such as the southwest. Based on data observed between 1999 and 2006, the cost per kilometer of trackline ranged between \$13 and \$24 and averaged \$18 (Table 1).

We model the relationship between cost and precision sampling for $N_{min}$ by observing how $CV_{Nbest}$ varies with the kilometers of aerial trackline surveyed ($x_1$; Figure 3). In general, an increase in surveyed trackline results in a decrease in the $CV_{Nbest}$ (Palka 2006). Although either variable ($x_1$ or $CV_{Nbest}$) can be estimated given the other, in the model we used the inverse

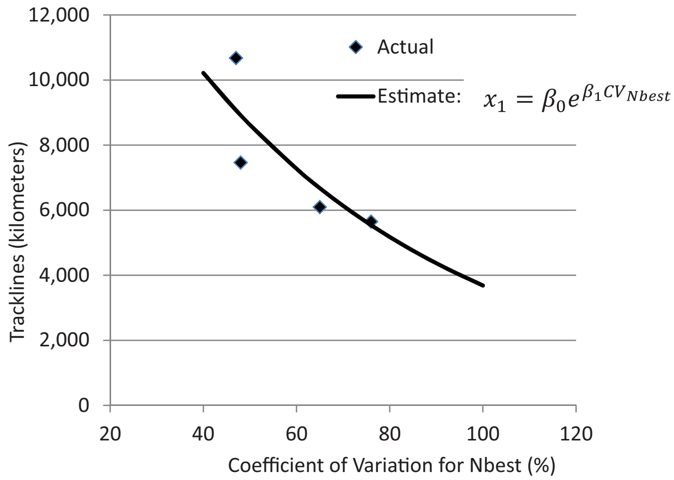


FIGURE 3. Observed kilometers of aerial trackline surveyed ($x_1$) in relation to the corresponding CV of the harbor porpoise abundance estimate ($\mathrm{CV}_{Nbest}$; diamonds) for 1999, 2002, 2004, and 2006.

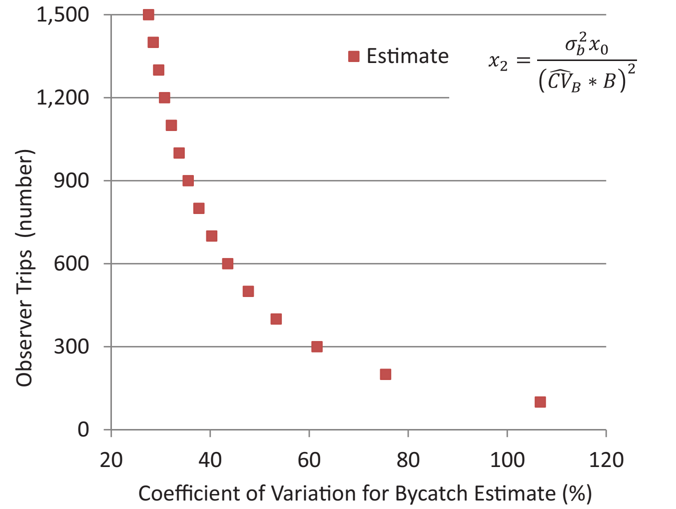


FIGURE 4. Total number of observer trips ($x_2$) in relation to the corresponding estimated CV of harbor porpoise bycatch ($\mathrm{CV}_B$). This is based on the 2008 northeast bycatch estimate ($B$) of 666 harbor porpoises ($\mathrm{CV}_B = 48\%$) from 494 observed trips ($x_0$).

relationship $x_1 = \beta_0 e^{\beta_1 \mathrm{CV}_{Nbest}}$ (with parameter estimates of $\beta_0 = 20{,}167$, $P = 0.002$; and $\beta_1 = -0.017$, $P = 0.144$), which had an $R^2$ value of 72%. Since $N_{min}$ is a function of $\mathrm{CV}_{Nbest}$, the tradeoffs between tracklines and sampling precision are embedded in the PBR formula.

*Observer program*.—The 2008 estimate of harbor porpoise bycatch in the northeast sink gill-net fishery was 666 animals ($\mathrm{CV}_B = 48\%$) based on 494 observed trips (Orphanides 2009). Observer data are necessary to estimate the total annual bycatch of harbor porpoises. The NMFS places third-party observers on a sample of commercial fishing vessels, and these observers collect biological data on the incidental takes of protected species as well as retained and discarded fish. The cost of an observer trip is approximately \$1,050 per trip, which includes the observer labor, training, gear, travel, and other direct overhead costs as well as data entry and editing in a database (A. Van Atten, NMFS, Northeast Fisheries Science Center [NEFSC], personal communication).

The observer data are used to estimate a sample bycatch rate ($b$) in terms of the number of harbor porpoises per observed fishing trip. To estimate the total bycatch ($B$), the estimated $b$ is multiplied by the total number of fishing trips in the population ($F$): that is, $B = F \times \mathrm{E}(b)$, where $F$ is known and $\mathrm{E}(b)$ is the expected bycatch rate. To estimate the $\mathrm{CV}_B$, we use the SD of the sampling distribution of $b$ ($\sigma_b$), which is a function of the number of observed trips in the original sample ($x_0$; NMFS 2005). As we increase the number of observed trips ($x_2$), we expect the new $\widehat{\mathrm{CV}}_B = (\hat{\sigma}_b/B)$ to decrease, all else held constant, where $\hat{\sigma}_b = \sqrt{\sigma_b^2[x_0/x_2]}$). Using Orphanides' (2009) harbor porpoise bycatch estimates with all else held constant, the rate of reduction in $\mathrm{CV}_B$ diminishes as the effort increases (i.e., the slope of the curve is steeper at lower effort levels; Figure 4).

Increased confidence in the bycatch estimate from a lower $\widehat{\mathrm{CV}}_B$ can translate into a higher estimate of PBR through $Fr$. In the model, we use a continuous approximation of the step function described for $Fr$ (see *Potential Biological Removal Calculation*). Given the narrow range for $Fr$ (0.4–0.5), the estimated linear function is quite flat. The relationship is $Fr = f(\widehat{\mathrm{CV}}_B)$—specifically, $Fr = \beta_0 + \beta_1 \cdot \widehat{\mathrm{CV}}_B$ (where $\beta_0 = 0.559$, $P = 0.002$; and $\beta_1 = -0.181$, $P = 0.05$), with an $R^2$ of 90%.

*Optimal allocation of public sector expenditures*.—Higher levels of funding are capable of producing lower levels of uncertainty. The objective is to minimize the total cost (TC) of acquiring biological data through the allocation of expenditures for abundance surveys and observed fishing trips at a given PBR level and a constant population estimate ($N_{best}$). We use estimates of $\widehat{\mathrm{CV}}_{Nbest}$ and $\widehat{\mathrm{CV}}_B$ from the equations above to measure the level of uncertainty associated with different levels of abundance survey tracklines and observer trips, which had different costs. Repeatedly solving the cost-minimization problem for different PBR levels allows us to trace out the TC curve. For notational simplicity, the $i$th PBR level is represented as $P_i$.

We solve the nonlinear cost-minimization problem for the two decision variables—kilometers of trackline surveyed ($x_1$) and number of observer trips ($x_2$)—subject to a given $P_i$ as follows:

$$\text{Minimize TC} : \mathrm{TC}_{P_i} = c_1 x_1 + c_2 x_2 \tag{3}$$

subject to

$$N_{min}[\widehat{\mathrm{CV}}_{Nbest}(x_1)] \times (0.5R_{max}) \times \{Fr[\widehat{\mathrm{CV}}_B(x_2)]\} \le P_i,$$

where $x_1 \ge 0$, $x_2 \ge 0$, $0.40 \le \widehat{\mathrm{CV}}_{Nbest} \le 1.00$, $0.30 \le \widehat{\mathrm{CV}}_B \le 1.00$, $R_{max} = 0.04$, $N_{best} = 89{,}000$, and $i = 1, 2, \ldots$ $N$ ($N$ is the number of PBR levels examined with our model). For simplicity, we suppress this additional notation on the decision variables ($x_1$ and $x_2$). The average cost per kilometer of trackline surveyed ($c_1$) from a Twin Otter plane is \$18, and the average cost per observed fishing trip ($c_2$) is \$1,050 (see *Abundance Surveys* and *Observer Program*). The $\widehat{\mathrm{CV}}_{Nbest}$ and $\widehat{\mathrm{CV}}_B$ are constrained, with the lower bound based on the levels observed and the upper bound based on levels that are considered acceptable from a scientific perspective (Waring et. al. 2006, 2009). Lower CVs may be achievable with other survey techniques and stocks; however, these are the minimums that have been attained for this particular harbor porpoise stock and survey method. For bycatch, *Fr* constrains the lower bound of $\mathrm{CV}_B$ to 30%. We also chose to not allow the $\mathrm{CV}_{Nbest}$ to extend outside the range of the observed data.

The solution to the cost-minimization problem produces the optimal kilometers of trackline to survey ($x_1^*$) and optimal number of observed fishing trips ($x_2^*$), which provide solutions for $\mathrm{CV}^*_{Nbest}$ and $\mathrm{CV}^*_B$ for a given $P_i$. This empirically traces out a direct connection between the cost of scientific information to a marine mammal management action or decision (Figure 1).

## Benefits to the Fishing Sector

Potential biological removal can result in constraints being placed on the private fishing sector, and relaxing those constraints can generate benefits in the form of increased profits. The private fishing sector responds to management changes in PBR by changing the amount and location of fishing effort, and these alterations in fishing behavior affect the profits of fishing ("economic outcomes"). The benefits of an increase in PBR are estimated via a numerical bioeconomic model of the sink gillnet fleet; for details on the model, see Bisack and Sutinen (2006) and Bisack (2008).

The model stratifies the fleet by season and port group. The fleet as a whole behaves as if it is attempting to maximize profits over the year, subject to a total harbor porpoise cap ($P_i$) set by management. Trip-level equations are estimated from the vessel-based observer program, and the model is expanded and calibrated to fleet-level catch data. Compared with the baseline, a lower $P_i$ will limit the number of fishing trips that can occur in season-ports where harbor porpoise bycatch occurs, and this can result in reduced or lower-valued landings and thus forgone profits. Alternatively, an increase in $P_i$ allows the fishing industry to relax previous restrictions and potentially increase profits, leading to a benefit over the previous (lower) cap level.

The changes in profits are translated to a marginal willingness to pay (WTP) for one more unit of harbor porpoise, which provides additional fishing opportunities and profit. This represents a demand function for additional bycatch and associated fishing opportunities. As the harbor porpoise cap becomes scarcer (lower), the WTP for an individual unit of harbor porpoise increases. Use of the WTP function allows for interpolation of changes in total fleet profit at different $P_i$ levels without rerunning the original model.

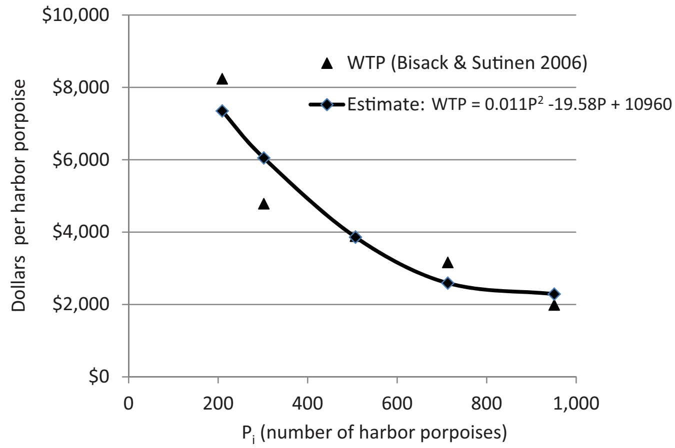


FIGURE 5. Willingness-to-pay (WTP) values (diamonds) for a unit of harbor porpoise at different potential biological removal ($P_i$) levels (Bisack and Sutinen 2006), converted to 2009 dollars with fitted equation (line).

The total benefits ($\mathrm{TB}_{P_i}$) for a change in the harbor porpoise cap from $P_{i-1}$ to $P_i$ is defined as follows:

$$\mathrm{TB}_{P_i} = \sum_{i}^{N} \mathrm{WTP}_{P_i}(P_i - P_{i-1}), \tag{4}$$

where $\mathrm{WTP}_{P_i} = \beta_0 + \beta_1 P_i + \beta_2 P_i^2$. Bisack and Sutinen's (2006) estimates for the price of one unit of the harbor porpoise cap range from \$2,000 (for a cap of 951 animals) to over \$8,000 (for a cap of 209 animals; Figure 5). We adjust the earlier model price values for inflation using the 2009 gross domestic product implicit price deflator. The point data are used to fit a quadratic function for $\mathrm{WTP}_{P_i}$, with coefficient estimates of $\beta_0 = 10{,}960$ ($P = 0.05$), $\beta_1 = -19.58$ ($P = 0.22$), and $\beta_2 = 0.011$ ($P = 0.36$), resulting in an $R^2$ value of 88%.

## Bringing Costs and Benefits Together

We use the concept of NB to illustrate the economic tradeoff between the costs to reduce scientific uncertainty and the private benefits available to the fishing sector by a reduction in restrictions as uncertainty is reduced. Net benefits are the difference between the optimal TC and the TB. The objective of an economic analysis is to find an efficient outcome that maximizes the net benefits to society from an activity.

Therefore, NB for the *i*th harbor porpoise cap, $P_i$ (i.e., PBR level), are defined as follows:

$$\mathrm{NB}_{P_i} = \mathrm{TB}_{P_i} - \mathrm{TC}_{P_i}. \tag{5}$$

For ease of presentation, we present the results in terms of TC and TB curves, with the maximum defined by the difference between the two. However, the maximization of NB is also the intersection of a marginal benefit curve and marginal cost curve. The private sector demand curve for harbor porpoises represents the marginal benefit to the private sector for an additional unit of the harbor porpoise cap. The public sector optimization creates a marginal cost curve of supplying the harbor porpoise cap, with all things unchanged except the two inputs (abundance survey tracklines and observer trips). The intersection of the two curves describes the static maximization of NB.

## RESULTS

### Costs for Information Collection

The results were attained by re-running the cost-minimization model with different $P_i$ levels. Feasible solutions were found for a narrow range of $P_i$ values between 354 and 643 harbor porpoises when the $CV_{Nbest}$ and $CV_B$ were at their maximum and minimum values, respectively (Table 2). Throughout the analysis, $N_{best}$ was set at 89,000 animals; however, with $R_{max}$ at 0.04 and the CV boundaries imposed, the PBR formula constrains the $P_i$ values to between 0.40% and 0.72% of any $N_{best}$ value.

The use of a continuous equation for *Fr* implicitly defined the minimum amount of observer coverage as 147 trips when the $CV_B$ reached 88% and with *Fr* equal to 0.040. This also meant that the upper bound constraint on $CV_B$ was not binding, as the *Fr* equation restricted $CV_B$ from exceeding 88%. With the step function (see *Potential Biological Removal Calculation*), *Fr* reached 0.4 when $CV_B$ was higher than 80%, meaning that cost savings could be achieved by allowing for a higher $CV_B$ and fewer observer trips without a reduction in *Fr* or PBR. The minimum *Fr* value with corresponding $CV_B$ and observer trips defines the lowest PBR value as 354 harbor porpoises when $CV_{Nbest}$ is constrained to its maximum. The continuous equation for *Fr* also implicitly defines a maximum number of observer trips as 1,049 trips when $CV_B$ is at 32.9% and when *Fr* equals 0.5. This constrains the upper range of $P_i$ to 643 animals.

The results from the cost minimization indicate that for the range of $P_i$ values examined, the cost-effective action is to increase the amount of tracklines and thus lower the $CV^*_{Nbest}$. To allow for a higher $P_i$, the optimization first incorporates more tracklines to reduce $CV^*_{Nbest}$ if possible. When $CV_{Nbest}$ is at its minimum (i.e., 40% when $P_i = 550$ animals), an increase in observer trips is necessary to further increase $P_i$. Although the cost of tracklines to improve precision may be lower, both tracklines and observer trips are modeled as necessary inputs to the calculation of $P_i$; the number of observer trips cannot fall below the minimum of 147 to achieve a $CV_B$ of 88%, and the trackline distance surveyed cannot fall below 3,711 km for a $CV_{Nbest}$ of 99.6%.

TABLE 2. Results of cost minimization for information collected at different potential biological removal ($P_i$) levels for harbor porpoises: total cost, kilometers of trackline ($x_1$), number of observer trips ($x_2$), and the recovery factor (*Fr*), CV for bycatch ($CV_B$), and CV for the abundance estimate ($CV_{Nbest}$) achieved given the choice variables.

| $P_i$ | Total cost (thousands of dollars) | $x_1$ | $x_2$ | *Fr* | $CV_B$ | $CV_{Nbest}$ |
|---|---|---|---|---|---|---|
| 354 | 221.0 | 3,711 | 147 | 0.400 | 88.0 | 99.6 |
| 400 | 251.7 | 5,414 | 147 | 0.400 | 88.0 | 77.4 |
| 450 | 287.8 | 7,421 | 147 | 0.400 | 88.0 | 58.8 |
| 500 | 326.3 | 9,561 | 147 | 0.400 | 88.0 | 43.9 |
| 550 | 408.8 | 10,216 | 214 | 0.427 | 72.8 | 40.0 |
| 560 | 437.9 | 10,216 | 242 | 0.435 | 68.6 | 40.0 |
| 600 | 636.0 | 10,216 | 431 | 0.466 | 51.4 | 40.0 |
| 643 | 1,285.0 | 10,216 | 1,049 | 0.499 | 32.9 | 40.0 |

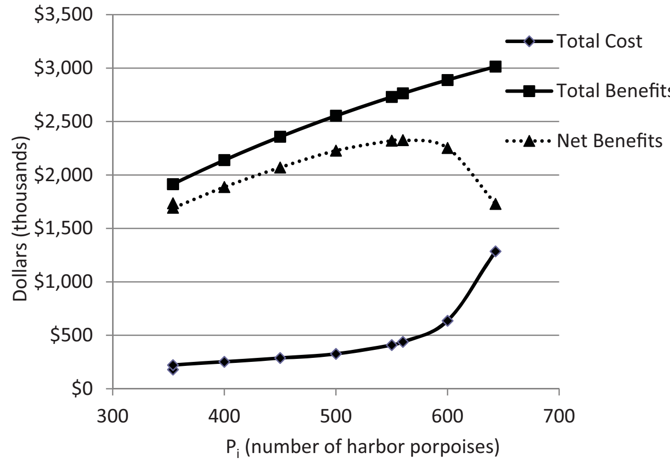


FIGURE 6. Empirical example showing that the total benefits to the fishing sector from increased profits at higher potential biological removal ($P_i$) levels for harbor porpoises exceed the total cost of the data collection necessary to increase the precision of PBR input variables, thus allowing for higher $P_i$ levels under a fixed population estimate. Total net benefits are the difference between total cost and total benefits and are maximized here at 545 animals.

To move beyond a $P_i$ of 500 animals, it is only possible to increase precision by increasing the number of observer trips, resulting in a rapid increase in costs (Figure 6). The cost per unit of $P_i$ increases from an average of \$770 between 450 and 500 animals ([\$326,300–\$287,800]/50) to an average of \$15,000 between 600 and 643 animals. Beyond 643 animals, the use of additional tracklines or observer trips would result in increased costs without an increase in $P_i$, as the CVs are unchanged due to their lower bound constraints.

### Bringing Costs and Benefits Together

Total fishing sector benefits from increases in $P_i$ (see *Observer Program*), are derived from the model of Bisack and Sutinen (2006). Total benefits range from \$1.914 million for a $P_i$ of 354 animals to \$3.016 million for a $P_i$ of 643 animals (Figure 6). This is based on values that ranged between \$5,407 per animal (at $P_i = 354$ animals) and \$2,918 per animal (at $P_i = 643$ animals); as $P_i$ increases, the value per animal decreases.

Net benefits are calculated as the difference between TB and TC. At all $P_i$ between 354 and 643 animals, the total public sector costs of collecting additional scientific data to increase precision and thus increase $P_i$ are lower than the TB to the private sector from such an increase (Figure 6). In this specific example, maximum economic NB occur at a PBR value of 560 animals. Beyond this point, TB still exceed TC; however, the cost of collecting additional scientific data increases faster than profits increase.

## DISCUSSION

In the USA, the public sector fully funds biological assessments for marine mammals. Funding shortfalls can delay or reduce the scale and frequency of abundance surveys (Simpkins and Srinivasan 2013) and can constrain the number of deployed observer trips. Reduced funding may lead to lower precision in key PBR input variables, resulting in a more conservative PBR value and potentially higher economic costs to society. The framework developed in this paper demonstrates that methods and data exist to assess the economic tradeoffs associated with funding for biological assessments and to estimate an economic value for scientific information.

No matter who is paying, over the range of PBR levels evaluated it is more cost effective to increase PBR by increasing tracklines to obtain a lower $CV^*_{Nbest}$ than to increase the number of observer trips to achieve a lower $CV^*_B$ (Table 2). In other words, a dollar that is spent on the abundance survey to increase tracklines yields a greater increase in PBR than a dollar that is spent on observer trips. This is dependent on the cost differential between observer trips and tracklines per unit change in their respective CVs and is also a function of the way in which the CVs enter the PBR calculation. Both situations are likely to persist in many cases.

The empirical results suggest that in this two-sector case, throughout the range of PBR values examined, private benefits always exceed public costs. The private sector would be better off paying the costs of additional abundance survey tracklines, observer trips, or both in order to keep PBR higher. That is, the fishing industry has an economic incentive to help fund data collection for harbor porpoise PBR calculations. (However, if the population and productivity rate were in fact declining, PBR would decline even with $CV_{Nbest}$ and $CV_B$ set equal to zero. For example, the North Atlantic right whale *Eubalaena glacialis*, which is protected under the Endangered Species Act, has a PBR equal to 1 [Waring et al. 2009]. This would remove any incentive for the private sector to contribute funds to data collection.) Although benefits to the fishing sector increase with PBR, so do the costs of obtaining the data to allow for that increase. For PBR values greater than 500 animals, the only way to increase precision is to add observer trips at a much higher cost per unit change in PBR than using aerial surveys; at a PBR of 560 animals, the total NB are at a maximum. Thus, the economically efficient level of PBR is below the upper end of the PBR range. This conclusion incorporates a number of assumptions that may result in an overstatement of the costs and benefits; however, the representations are reasonable for illustrating the framework.

This analysis may overstate the public cost for a number of reasons. Both abundance surveys and observed fishing trips deliver research information on multiple species. While abundance surveys may target a particular species (e.g., the harbor porpoise) to estimate encounter rates, data are collected for all marine mammals and marine megafauna (e.g., sea birds, sharks, and turtles). However, the data collected may not be statistically sound for obtaining additional species abundance estimates. For species with a low CV value (species frequently seen), the design needs fewer sea days in comparison with species that have a higher CV (species rarely seen). A manager's high-priority species list with corresponding CVs of animal encounter rates could be used to determine how many species can be assessed adequately for a given budget year. Similarly, observers on commercial fishing trips collect catch data on multiple species, including bycatch and target species. Sampling priorities will also produce different CVs for commercial fishery catch rates. If there are economic efficiencies from collecting data for multiple species, this may provide even *more* incentive for the private sector to participate in marine mammal research so as to ensure regular surveys and estimates with lower variance.

Additionally, public costs for the abundance estimate could be reduced with the use of multiple survey platforms and new design methods that increase precision. In the case of the 1999 two-platform (shipboard and aerial) survey, the combined $CV_{Nbest}$ was substantially lower at 22%; however, the costs per unit of trackline were high. To date, there have only been two surveys of such magnitude in the northeast USA (Palka 2012). The 1999 combined ship and aerial survey for harbor porpoises cost roughly \$380,000 (\$285,000 ship + \$95,000 aerial; D. Palka, NMFS, NEFSC, personal communication), and the cost per kilometer of trackline surveyed was \$111 ($CV_{Nbest} = 15\%$) for the ship versus \$17 ($CV_{Nbest} = 76\%$) for the plane (overall $CV_{Nbest} = 22\%$). Additional multi-cetacean survey designs have been proposed as well as new methodologies and technologies (C. Werner, paper presented at the National Marine Fisheries Service Board Meeting, 2012). For example, a new methodology for the harbor porpoise aerial survey was implemented in 2011, but it was not comparable with previous survey methods (Palka 2012) and was therefore not included in this analysis. Although the combined platform surveys or new methodologies may result in higher per-unit costs, it is possible that the impact on $CV_{Nbest}$ could result in economic NB; however, multiple data points are required to determine this relationship.

A number of factors could also affect the private sector benefit analysis. We did not analyze the implications of transaction costs and alternative bycatch reduction techniques. Implicitly, we assume that transaction costs are zero for the transfer of funds from the private sector to the public sector. The higher are the transaction costs, the lower is the economic incentive for the private sector to contribute to scientific data collection. The dispersed gill-net fleet along the U.S. east coast could make the collection and transfer of funds difficult to organize; however, it is possible that funding could be organized through fishery management plans (e.g., the Research Set-Aside Program; www.nefsc.noaa.gov/coopresearch/rsa_program.html). Additionally, gear modifications and technological advances may provide lower-cost alternatives to reducing bycatch than shifting effort, as modeled by Bisack and Sutinen (2006). If fishers are able to mitigate the impacts of bycatch reduction through less costly actions, there would be fewer benefits from a higher PBR. This would lower the value of scientific information to the fishing sector, as the gain in profits from higher precision would be lower.

Underfunding of surveys can result in a net economic loss to society, as demonstrated here. To plan for funding shortfalls, the Proposed Guidelines for Assessing Marine Mammal Stocks (Moore and Merrick 2011) formally addressed how outdated stock assessments should be handled. As the abundance estimates age, our knowledge about the stock decreases. This is reflected by the increased variance ($CV^*_{Nbest}$) around the point estimate, $N_{best}$, while the point estimate is left constant. The result is a lower PBR for a given $N_{best}$ estimate. The problem could be compounded further if there is an increase in the true abundance due to the success of past protection practices. Thus, in the absence of regular abundance surveys, it is not possible to determine whether changes in bycatch rates from observed fishing trips are due to (1) behavioral changes in the fishing fleet or the animals or (2) an increase in abundance of the animals. This may be an incentive for the private fishing sector to put pressure on the public sector to conduct assessments more frequently.

The present analysis did not include an examination of the value of information from life history assessments to marine mammal management. Changes in $R_{max}$ from the default value are rare, occurring only if there is some resounding evidence from the peer-reviewed literature that the value has changed. Such was the case for harbor porpoises during the 2009 stock assessment (Waring et al. 2009). Life history assessments, which may result in a change in the estimate of $R_{max}$, are part of longer-term research and are also subject to funding availability. Potential biological removal is strongly influenced by changes in $R_{max}$ estimates, such as those completed by Moore and Read (2008). Potential biological removal increased by almost 100 animals when $R_{max}$ increased from 0.040 to 0.046. The scale of the impact on PBR suggests that more assessments may be appropriate.

We do not attempt to describe the full social NB anticipated from marine mammal protection. The existence of the MMPA suggests that the American public as a whole places a positive value on marine mammals. A full analysis of social NB would include an estimate of the dollar amount the American public is willing to pay (i.e., WTP) to protect one or more harbor porpoises. McConnell and Strand (1997) determined that the value placed on harbor porpoises is statistically different between the American public and scientists in the northeast; however, we could not translate the results into a form useable in this study. A positive WTP by the public to avoid bycatch of harbor porpoises would reduce the total NB since each unit of bycatch would have an associated cost. Depending on the scale of public WTP compared with fishing sector profits, it is possible that the economic incentive to move to higher PBR values could be reversed.

Our analysis provides interesting first results, but further research is necessary to determine the ability to generalize these results. To demonstrate the case of the harbor porpoise, we used a WTP curve (shadow value) based on previous research (Bisack and Sutinen 2006) and updated the values to 2009 dollars; however, management regimes for harbor porpoises and fish have changed. Bycatch of harbor porpoises in the Mid-Atlantic has become a larger component of overall bycatch (Waring et al. 2009), whereas the WTP curve is only for the northeast. To calculate more precise tradeoff measures, the model would have to be updated and expanded. However, we do not expect different qualitative findings: we expect that the results will continue to show that the value of scientific information to the private sector exceeds the costs of funding surveys.

Within our model, the public and private sectors consider different economic problems in the management of marine mammal bycatch. The public sector is minimizing costs to collect scientific data that are necessary to meet regulatory requirements. The objective of the private sector is to maximize profits within management constraints, such as PBR. The results of this work could inform the budget process and lead to a more efficient allocation of resources for the public sector. Our results suggest that the private fishing industry may want to contribute to funding the collection of scientific data on marine mammals to reduce uncertainty, thereby allowing for a higher PBR.

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## REFERENCES

Bisack, K. D., and J. G. Sutinen. 2006. Harbor porpoise bycatch: ITQs or time/area closures in the New England gillnet fishery. Land Economics 82:85–102.

Bisack, K. D. 2008. Integrating porpoise and cod management: a comparison of days-at-sea, ITQs and closures. Marine Resource Economics 23:361–378.

Buckland, S. T., D. R. Anderson, K. P. Burnham, and J. L. Laake. 1993. Distance sampling: estimating abundance of biological populations. Chapman and Hall, London.

FAO (Food and Agriculture Organization). 1996. Precautionary approach to capture fisheries and species introductions. FAO, Technical Guidelines for Responsible Fisheries 2, Rome.

Hildreth, R. G., M. C. Jarman, and M. Langlas. 2004. Roles for a precautionary approach in U.S. marine resources management. Natural Resources and Environment 19:64–67.

Huppert, D. D. 1996. Risk assessment, economics, and precautionary fisheries management. FAO (Food and Agriculture Organization of the United Nations) Fisheries Technical Paper 350:103–128.

McConnell, K. E., and I. E. Strand. 1997. Northeastern harbor porpoises: do scientists' perceptions reflect the publics'? Ambio 26:124–125.

MMPA (Marine Mammal Protection Act). 1972. U.S. code, volume 16, sections 1361–1407.

Moore, J. E., and R. Merrick, editors. 2011. Guidelines for assessing marine mammal stocks: report of the GAMMS III workshop. NOAA Technical Memorandum NMFS-OPR-47.

Moore, J. E., and A. J. Read. 2008. A Bayesian uncertainty analysis of cetacean demography and bycatch mortality using age-at-death data. Ecological Applications 18:1914–1931.

NMFS (National Marine Fisheries Service). 2005. Revisions to guidelines for assessing marine mammal stocks. Available: http://www.nmfs.noaa.gov/pr/pdfs/sars/gamms2005.pdf. (August 2013).

NOAA (National Oceanic and Atmospheric Administration). 2006. Environmental assessment, regulatory impact review and final Regulatory Flexibility Act analysis for a final rule to implement the Bottlenose Dolphin Take Reduction Team Plan and revise the large mesh size restriction under the Mid-Atlantic Large Mesh Gillnet Rule. April 2006. Available: http://www.nmfs.noaa.gov/pr/pdfs/interactions/bdtrp_ea.pdf. (August 2013).

NOAA (National Oceanic and Atmospheric Administration). 2009. Modifications to the Harbor Porpoise Take Reduction Plan. Final environmental assessment (includes regulatory review and final regulatory flexibility analysis). September 2009. Available: http://www.nero.noaa.gov/nero/regs/frdoc/10/10HPTRP_GOMBF_EA.pdf. (August 2013).

NOAA (National Oceanic and Atmospheric Administration). 2012. Environmental assessment, regulatory impact review and final Regulatory Flexibility Act analysis for a final rule to implement the False Killer Whale Take Reduction Plan. November 2012. Available: http://www.fpir.noaa.gov/Library/PRD/False%20Killer%20Whale/FKWTRP%20Final%20EA-RIR-FRFA%20and%20FONSI%20%2811-15-2012%29.pdf. (August 2013).

Orphanides, C. D. 2009. Protected species bycatch estimating approaches: estimating harbor porpoise bycatch in U.S. northwestern Atlantic gillnet fisheries. Journal of Northwest Atlantic Fishery Science 42:55–76.

Palka, D. 2006. Summer abundance estimates of cetaceans in U.S. north Atlantic navy operating areas. Northeast Fisheries Science Center, Reference Document 06-03, Woods Hole, Massachusetts.

Palka, D. 2012. Cetacean abundance estimates in U.S. northwestern Atlantic Ocean waters from summer 2011 line transect survey. Northeast Fisheries Science Center, Reference Document 12-29, Woods Hole, Massachusetts.

Resolve. 1996. A final draft Gulf of Maine/Bay of Fundy Harbor Porpoise Take Reduction Team take reduction plan - a consensus document. August 1996. Prepared for the National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Regional Office, Protected Resource Division, Gloucester, Massachusetts. Available: http://www.nero.noaa.gov/prot_res/porptrp/HarborPorpoiseTRP.pdf. (August 2013).

Simpkins, M., and M. Srinivasan, editors. 2013. Report of the protected resources science investment plan workshop. Available: http://spo.nmfs.noaa.gov/tm/TM130.pdf. (August 2013).

U.S. Department of Commerce. 1998. Taking of marine mammals incidental to commercial fishing operations; harbor porpoise take reduction plan regulations. Federal Register 63:231(2 December 1998):66464–66490.

U.S. Department of Commerce. 2010. Taking of marine mammals incidental to commercial fishing operations incidental to commercial fishing operations; harbor porpoise take reduction plan regulations. Federal Register 75:33(19 February 2010):7383–7402.

U.S. Department of Commerce. 2012. Guidelines for assessing marine mammal stocks. Federal Register 77:15(24 January 2012):3450–3453.

Wade, P. R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. Marine Mammal Science 14:1–37.

Wade, P. R., and R. P. Angliss. 1997. Guidelines for assessing marine mammal stocks: report of the GAMMS workshop. NOAA Technical Memorandum NMFS-OPR-12.

Waring, G. T., E. Josephson, C. P. Fairfield, and K. Maze-Foley, editors. 2006. U.S. Atlantic and Gulf of Mexico marine mammal stock assessments–2005. NOAA Technical Memorandum NMFS-NE-194.

Waring, G. T., E. Josephson, K. Maze-Foley, and P. E. Rosel, editors. 2009. U.S. Atlantic and Gulf of Mexico marine mammal stock assessments–2009. NOAA Technical Memorandum NMFS-NE-213.